(12) **UK Patent Application** (19) **GB** (11) **2 334 164** (13) **A**

(21) Application No 9902928.2

(22) Date of Filing 09.02.1999

(30) Priority Data
(31) 19805240   (32) 10.02.1998   (33) DE
(31) 19854789   (32) 27.11.1998

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(51) INT CL^6
H02M 3/10

(52) UK CL (Edition Q)
H3P PCCD
H3T T2B9 T2C T3F1
U1S S1883

(56) Documents Cited
WO 98/27600 A1   US 5479062 A   US 5387834 A
US 4628275 A

(58) Field of Search
UK CL (Edition Q) H3P PCCD
INT CL^6 H01L 41/04

(54) Abstract Title
A drift-compensated piezoelectric fuel injector actuator

(57) Because the capacitance of a piezoelectric actuator 1 changes with temperature and age, the charge delivered to it must be adjusted to achieve a consistent driving voltage and hence a consistent extension. The potential Up across the actuator after charging is measured and the operation of the half-bridge 3-6 in the subsequent charging cycle is adjusted accordingly. Alternatively, the charging time required to achieve a predetermined voltage may be measured and the charging current for the next cycle adjusted accordingly. Changes in the charging current can also be made within a charging cycle.
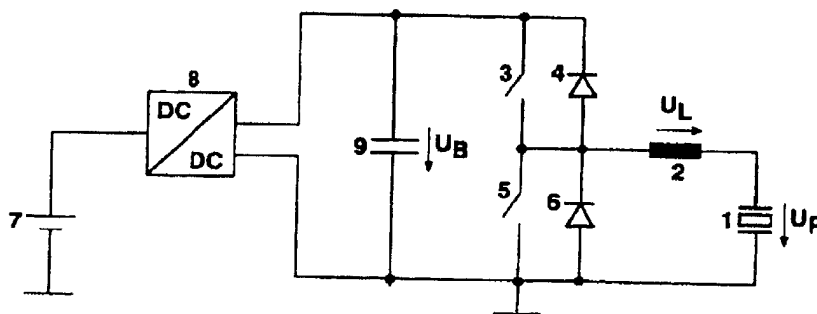

Fig. 1a

GB 2 334 164 A

Fig. 1a

Fig. 1b

U_L

U_B ↓ 9 $i_{LE}{}^{(t)}$ 1 ↓ U_P

FIG. 2

U_L

6 $i_{LA}{}^{(t)}$ 1 ↓ U_P

FIG. 3

U_L

$i_{EE}{}^{(t)}$ 1 ↓ U_P

FIG. 4

U_L

U_B ↓ 9 4 2 $i_{EA}{}^{(t)}$ 1 ↓ U_P

FIG. 5

FIG. 6

102 103 104 106 107 108

105 101
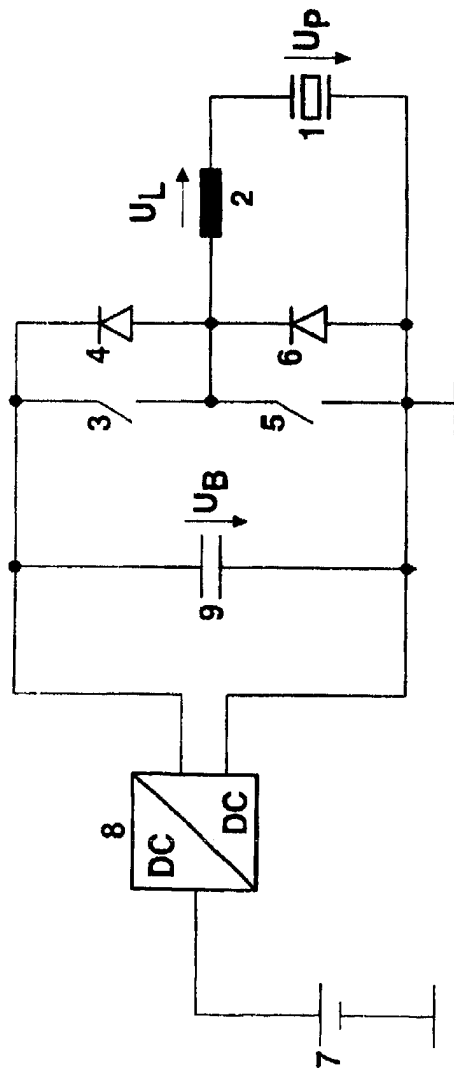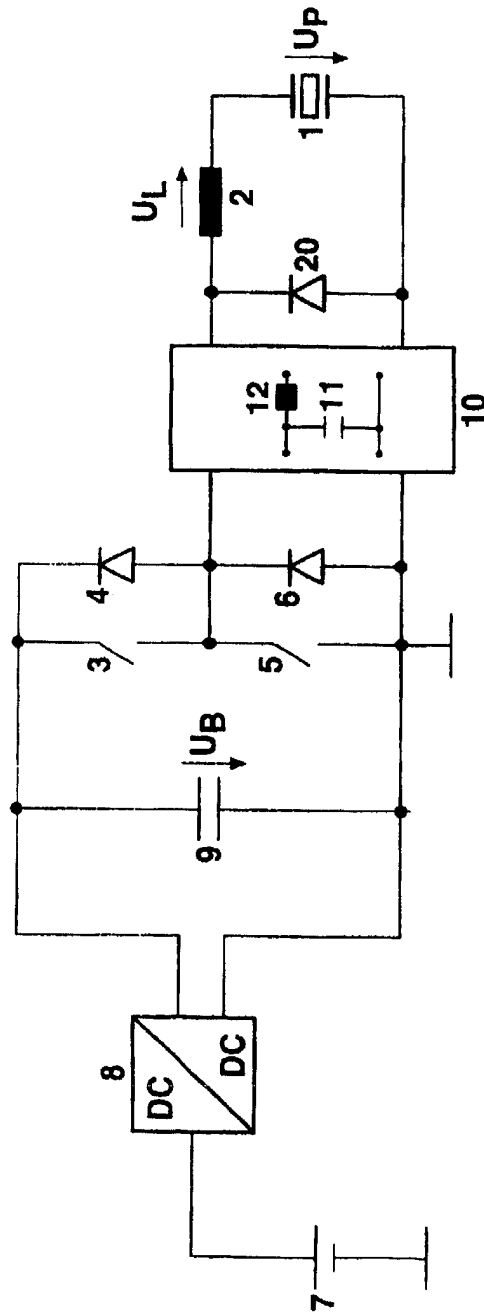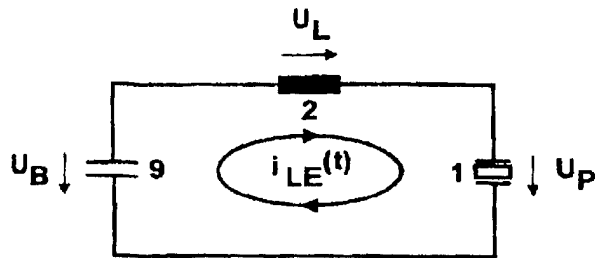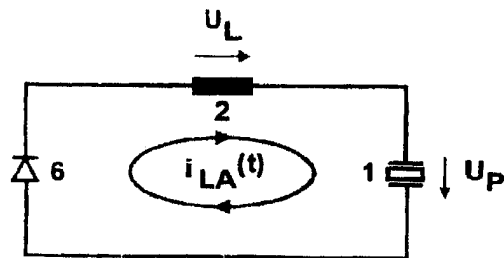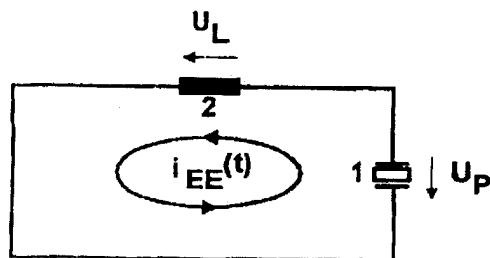
FIG. 7

Fig. 8

METHOD OF AND MEANS FOR INFLUENCING THE OPERATION OF A PIEZO-ELECTRIC ELEMENT

The present invention relates to a method of and device for influencing the operation of a piezo-electric element, especially in the charging and/or discharging of the element.

Piezo-electric elements are used as, inter alia, actuators or setting members. They are particularly suitable for purposes of that kind because, as is known, they have the property of contracting or expanding in dependence on a volt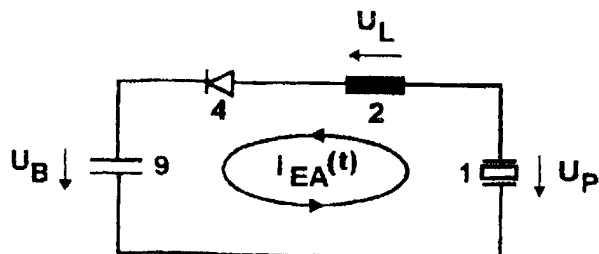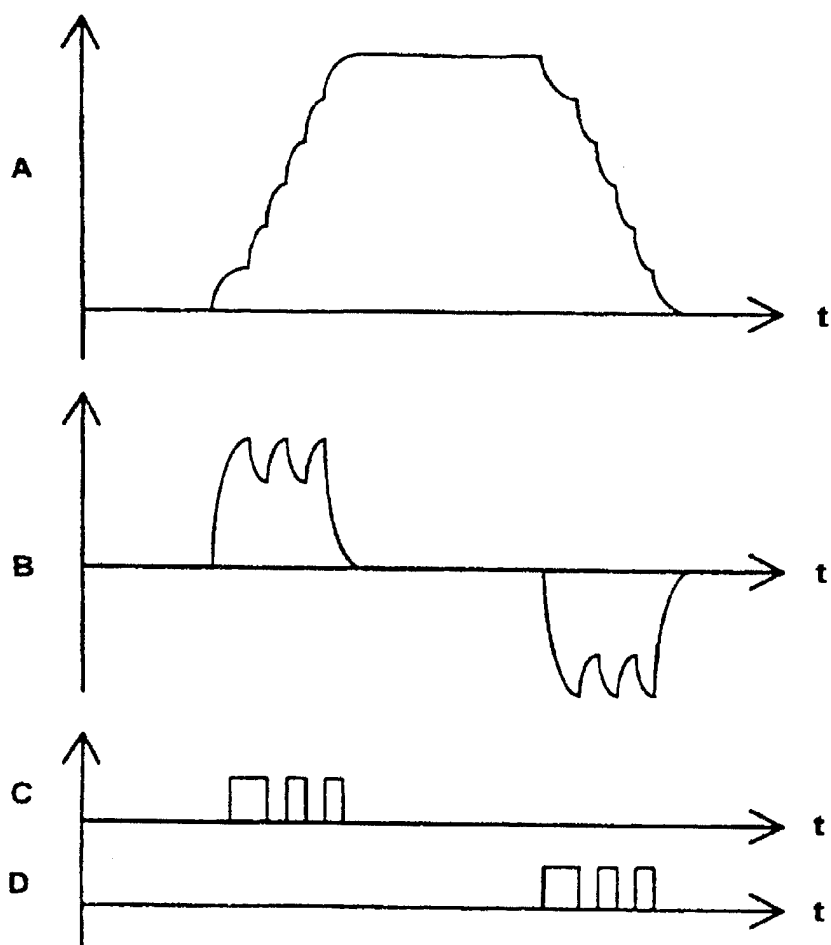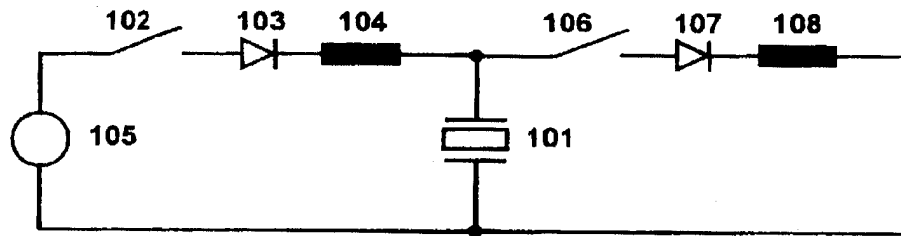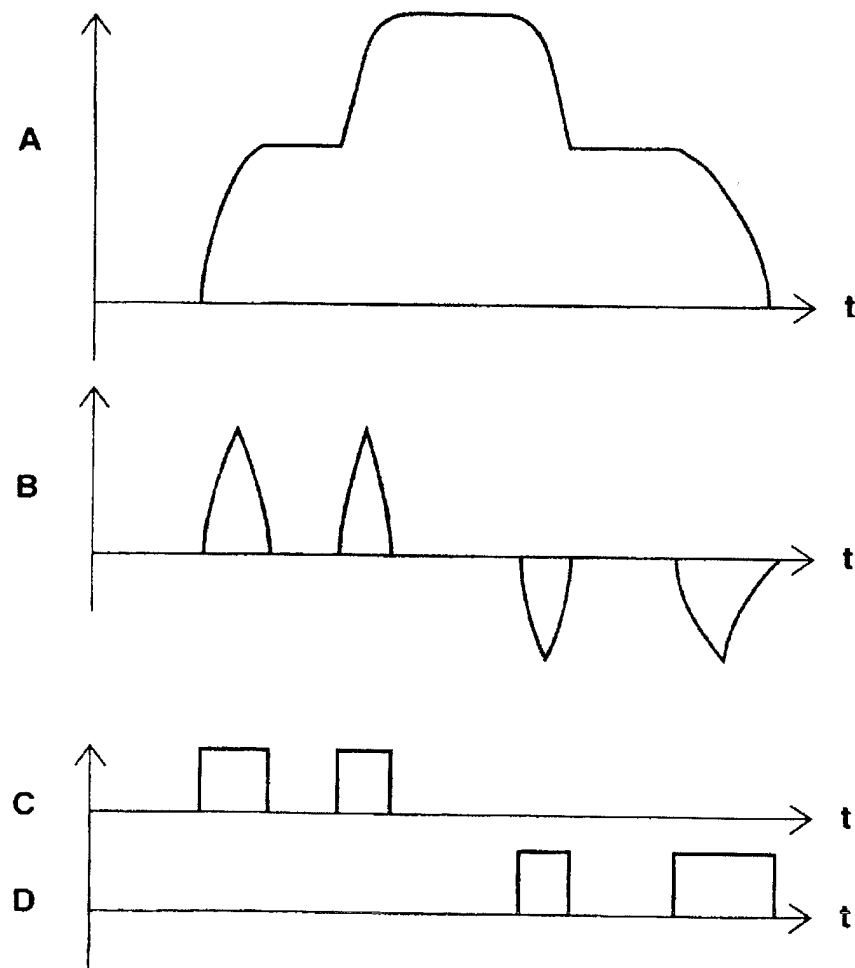age applied thereto. The realisation of settings members by piezo-electric elements is especially of advantage in the case of a setting member that has to execute rapid and/or frequent movements. Thus, the deployment of piezo-electric elements as setting members is advantageous in the case of fuel injectors for internal combustion engines. For the use of piezo-electric elements in this manner, reference is made to EP 0 371 469 B1 and EP 0 379 182 B1 by way of example.

Piezo-electric elements are capacitive loads which, as indicated above, contract or expand according to the respective state of charge or the voltage setting in or applied across the element. The charging and discharging of a piezo-electric element can take place by way of a component with inductive properties, for example a coil, wherein this coil serves primarily to limit the charging current occurring during charging and the discharging current occurring during discharging. Such an arrangement is illustrated in Fig. 7. In Fig. 7, the piezo-electric element 101 to be charged or discharged is a component of a charging current circuit closable by way of a charging switch 102 and a discharging current circuit closable by way of a discharge switch 106. The charging circuit consists of a series connection of the switch 102, a diode 103, a charging coil 104, the element 101 and a voltage source 105 and the discharging circuit consists of a series connection of the switch 106, a diode 107, a discharge coil 108 and the element 101.

The diode 103 prevents the current discharging the element 101 from flowing into the charging circuit. The diode 103 and the switch 102 can be a semiconductor switch. The diode 107 prevents the current charging the element 101 from flowing into the discharging circuit. The diode 107 and the switch 106, like the diode 103 and switch 106, can be a semiconductor switch.

If the normally opened switch 102 is closed, a current by which the element 101 is charged flows in the charging circuit. The charge stored in the element 101 or the voltage setting in across this and thereby also the actual external dimensions of element 101 are retained substantially unchanged after the charging. If the normally likewise open switch 106 is closed, a current by which the element 101 is discharged flows in the discharging current circuit. The charging state of the element 101 or the voltage setting in across this and thereby also the actual external dimensions of the element 101 are retained substantially unchanged after the discharging. The element 101 can thus be charged and discharged with relatively little effort by the arrangement shown in Fig. 7.

However, it is not possible with this and other such arrangements to allow the element to be charged and discharged in such a way that the state of charge of the element after the charging and discharging, and/or the time during which the element must be charged or discharged in order to reach a certain state of charge, will always assume exactly the desired value.

There is thus scope for developing a method and means whereby the charging and discharging of a piezo-electric element may be able to be performed rapidly and to the extent desired.

According to a first aspect of the present invention there is provided a method for charging and discharging a piezo-electric element in which the charging current charging the element or the discharging current discharging the element is set subject to consideration of the capacitance of the element.

According to a second aspect of the invention there is provided means for charging and discharging a piezo-electric element, the means comprising a control or regulating device which is designed for the purpose of setting either the charging current charging the element or the discharging current discharging the piezo-electric element subject to consideration of the capacitance of the element.

Thus, influences of tolerances and of variations and fluctuations of the capacitance of the piezo-electric element on the extent and speed of charging and discharging thereof can be eliminated. This is very significant because the capacitance of the piezo-electric element and thereby also the voltage setting in during the charging and discharging or the time

3

during which the element must be charged and discharged in order to reach a predetermined voltage and consequently also the change in length of the element depend on diverse factors such as, for example, the temperature, the force to be exerted by the element, the age of the element and so forth. By elimination of these dependencies, the state of charge of the element after the charging and discharging and/or the time for charging or discharging in order to achieve a certain state of charge always assumes or assume exactly the desired values.

This proves to be advantageous in two respects, on the one hand because the piezo-electric element always excites the system which contains it to exactly the same degree and on the other hand because the system is prevented from being set into oscillation due to deviation from the desired course of movement of the element (too rapid or too slow and/or too much or too little expansion or contraction.

Embodiments of the present invention will now be more particularly described by way of example with reference to the accompanying drawings, in which:

Fig. 1a   is a diagram of a first circuit for the charging and discharging of a piezo-electric element with settable charging or discharging current;

Fig. 1b   is a diagram of a second circuit for the charging and discharging of a piezo-electric element with settable charging or discharging current;

Fig. 2   is a diagram for explanation of the circuit conditions applicable in the circuit of Fig. 1a or 1b during a first charging phase;

Fig. 3   is a diagram for explanation of the circuit conditions applicable in the circuit of Fig. 1a or 1b during a second charging phase;

Fig. 4   is a diagram for explanation of the conditions applicable in the circuit of Fig. 1a or 1b during a first discharging phase;

Fig. 5   is a diagram for explanation of the conditions applicable in the circuit of Fig. 1a or 1b during a second discharging phase;

Fig. 6   is a set of diagrams showing voltage and current courses, plotted against time, in the circuit of Fig. 1a or 1b during operation;

Fig. 7   is a diagram of a conventional circuit for charging and discharging of a piezo-electric element, as already explained; and

Fig. 8   is a set of diagrams showing voltage and current courses, plotted against time, in the circuit of Fig. 1a or 1b.

Piezo-electric elements, the charging and discharging of which is described more closely in the following, are usable as, for example, setting members in fuel injection nozzles, in particular in common rail injectors, of internal combustion engines. However, there is no restriction on the employment of piezo-electric elements, which can be used for a wide variety of purposes. It is presupposed in the following description that the elements expand in response to charging and contract in response to discharging, but the opposite can be the case.

Referring now to the drawings, there is shown in Figs. 1a and 1b circuits in which a charging current charging a piezo-electric element 1 and a discharging current discharging the element are set subject to consideration of the capacitance of the element. As is evident from Fig. 1a, one of the terminals of the piezo-electric element 1 is constantly connected to ground, i.e. connected with a first pole of a voltage source, whereagainst the other one of the terminals of the element is connected by way of a coil 2, which acts as bot charging coil and discharging coil, and a parallel connection of a charging switch 3 and a diode 4 with the second pole of the voltage source and by way of the coil 2 and a parallel connection of a discharging switch 5 and a diode 6 with the first pole of the voltage source. The voltage source consists of a battery 7, for example a motor vehicle battery, a direct voltage converter 8 connected behind the converter and a capacitor 9 connected behind this and serving as buffer capacitor. In this arrangement, the battery voltage, for example 12 volts, is converted into any desired other direct voltage and provided as supply voltage.

A particularly advantageous embodiment is illustrated in Fig. 1b. Elements already described in Fig. 1a are identified by corresponding reference symbols. In this embodiment, a filter means 10 and a diode 20 are arranged between the switches 3 and 5 and the piezo-electric element 1. The anode of the diode 20 is connected with one

terminal of the element 1 and the cathode of the diode 20 is connected with the coil 2. The filter means 20 is connected on the one hand with the terminals of the diode 20 and on the other hand with the terminals of the diode 6.

The filter means connected at the output of the output stage causes a smoothing of the current courses and the voltage courses. The current and the voltage accordingly have a course corresponding to a resonator circuit drive and electromagnetic interferences can thereby be minimised. The peaks in the current course arising during the switching-off of the charging switch 3 and/or of the discharging switch 5 are smoothed.

The diode 20 has a protective function, in particular prevention of negative voltages which can damage the piezo-electric element.

In the circuit of Fig. 1b, the filter means 10 comprises an inductance 12 connected in series with the coil 2 and a capacitance 11 connected in parallel with the diodes 6 and 20.

The inductance 12, as well as the diode, can be omitted in a simplified embodiment. Components can also be saved by the coil 2 and the inductance 20 forming one constructional unit, i.e. merely one coil with a centre tap is provided.

The charging and the discharging of the element 1 take place in pulsed manner, i.e. the charging switch 3 and the discharging switch 5 can be repeatedly closed and opened during the charging or discharging operation.

The conditions applying in that case are explained in the following with reference to Figs. 2 to 5, of which the Figs. 2 and 3 illustrate charging of the element and Figs. 4 and 5 illustrate discharging of the element.

The charging switch 3 and the discharging switch 5 are open when and for as long as no charging or discharging of the piezo-electric element 1 takes place. In this state, the circuit shown in Fig. 1a or 1b is disposed in the steady state, i.e. the element retains its state of charge substantially unchanged and no currents flow. With the beginning of charging, the switch 3 is repeatedly closed and opened, whilst the discharging switch 5 remains opened.

The conditions shown in Fig. 2 set in on closing of the switch 3, i.e. a closed current loop is formed, which consists of a series connection of the piezo-electric element 1, the capacitor 9 and the coil 2 and in which a current $i_{LE}(t)$ flows, as indicated by arrows in Fig. 2. This current flow has the effect that energy is stored in the coil 2. The energy flow into the coil 2 is in that case caused by the positive potential difference between the capacitor 9 and the element 1.

During the opening of the charging switch 3, which takes place shortly after, for example some microseconds, closing of the same, the conditions shown in Fig. 3 set in, i.e. a closed current loop is formed, which consists of a series connection of the piezo-electric element 1, the diode 6 and the coil 2 and in which a current $i_{LA}(t)$ flows, as indicated by arrows in Fig. 3. This current flow has the effect that the energy stored in the coil 2 flows entirely into the element 1.

According to the energy supply to the element, the voltage setting in across this and its external dimensions increase. After energy transport has taken place from the coil 2 to the element, the steady state is reached again.

Then, or even previously or later (according to the desired time course of the charging operation), the charging switch 3 is closed again and opened once more, in which case the afore-described operations are repeated. Due to the renewed closing and opening of the charging switch 3, the energy stored in the element 1 increases - the energy already stored in the element and the newly supplied energy are added together - and the voltage setting in across the element and its external dimensions increase accordingly.

If the described closing and opening of the charging switch 3 is repeated a number of times, the voltage setting in across the element and the expansion thereof rise in stages; see for this the curve A of the Fig. 6 explained in greater detail later.

If the charging switch 3 has been closed and opened during a predetermined time and/or a predetermined number of times and/or the element has reached the desired state of charge, the charging of the element is terminated by leaving the charging switch 3 open.

If the element is to be discharged again, this is carried out by a repeated closing and opening of the discharging switch 5. The charging switch 3 remains opened in this case.

On closing of the discharging switch 5, the conditions shown in Figure 4 set in, i.e. a closed current loop is formed, which consists of a series connection of the element 1 and the coil 2 and in which a current $i_{EE}(t)$ flows, as indicated by arrows in Fig. 4. This current flow has the effect that the energy (a part thereof) stored in the piezo-electric element is transported into the coil 2. According to the energy transfer from the element to the coil, the voltage setting in across the element and its external dimensions decrease.

On opening of the discharging switch 5 shortly after, for example some microseconds, closing of the same, the conditions shown in Fig. 5 set in, i.e. a closed current loop is formed, which consists of a series connection of the element, the capacitor 9, the diode 4 and the coil 2 and in which a current $i_{EA}(t)$ flows, as indicated by arrows in Fig. 5. This current flow has the effect that the energy stored in the coil 2 is fed back entirely into the capacitor 9. After the energy transport has taken place from the coil 2 to the capacitor 9, the steady state of the circuit according to Fig. 1a or 1b is reached.

Then, or even earlier or later (according to the desired time course of the discharging operation), the discharging switch 5 is closed again and opened once more, in which case the afore-described operations are repeated. Due to the renewed closing and opening of the discharging switch 5, the energy stored in the element is further reduced and the voltage setting in across the element and the external dimensions thereof decrease accordingly.

If the described closing and opening of the discharging switch 5 is repeated a number of times, the voltage setting in across the element and the expansion thereof reduce in steps; see for this the curve A in Fig. 6.

If the discharging switch 5 has been closed and opened for a predetermined time and/or a predetermined number of times and/or the element has reached the desired state of discharge, the discharging of the element is terminated by leaving the discharging switch 5 open.

The extent and the course of the charging and discharging can be determined by the frequency and duration of the opening and closing of the charging switch 3 and discharging switch 5. This applies not only to the circuits shown in Figs. 1a and 1b, but to

all arrangements by which a comparable charging and/or discharging of piezo-electric elements can be performed. The arrangements must in that case be suitable substantially only for a keyed charging and discharging of one or several piezo-electric elements.

It is to be noted that arrangements such as that shown in Fig. 7 are not designed for keyed charging and/or discharging of the piezo-electric element. In that arrangement, the charging and discharging coils act as the inductive element of an inductance-capacitance series resonant circuit formed in co-operation with the piezo-electric element, wherein the inductance of the inductive element and the capacitance of the piezo-electric element alone determine the course and the extent of the charging and discharging. Charging and discharging can be carried out only with the first current half wave of the first resonant circuit oscillation, because a further oscillation of the resonant circuit is inhibited by the diodes contained in the charging current loop and discharging current loop.

By contrast, in the circuits designed for keyed charging and discharging, for example the circuits illustrated in Figs. 1a and 1b, the coil or other element with inductive properties is used as an intermediate energy storage device. This in alternation stores electrical energy, in the form of magnetic energy, supplied from the current supply source during charging or from the piezo-electric element during discharging and, after an appropriate switch actuation, delivers the stored energy in the form of electrical energy to the element during charging or another energy storage device or an electrical load during discharging, wherein the time instants and duration and thereby also the extent of storage and the energy delivery are determined by the switch actuation(s).

Thus, the piezo-electric element can be charged and discharged as far as desired in steps which are as many as desired, as large as desired and succeed at desired time spacings.

If the switch is opened and closed repeatedly in such a manner that the piezo-electric element is brought by a preset mean charging or discharging current to a preset voltage, the charging and discharging can be performed gently and is adaptible in simple manner to individual and changing conditions.

The actuation of the charging switch 3 and discharging switch 5 takes place by a control or regulating device, which is not shown in Fig. 1a or 1b. This device causes opening and closing of the switch 3 and switch 5 in such a manner that the element is brought to a

preset voltage whilst maintaining a preset mean (charging or discharging) current flow. For this purpose, the switch 3 and switch 5 are opened and closed at certain points in time, wherein the times during which the switches are closed and the times during which they are open can be of equal or different length and can be varied as desired even within a respective charging or discharging operation.

The charging or discharging current to set in is fixed subject to consideration of the capacitance of the piezo-electric element to be charged or to be discharged, wherein, however, the charging current and discharging current are kept substantially constant during a charging and discharging operation. Changes in the charging and/or discharging current which may be required can, however, also be performed during a charging or discharging operation.

The capacitance of the piezo-electric element, in dependence on which the charging current or the discharging current is to be varied, is not measured directly in the present embodiments, but determined by the extent to which the element expands or contracts during the charging or discharging. In that case, use is made of the recognition that the change in length of the element caused by the charging or discharging is proportional to the voltage setting in across the element due to the charging or discharging and that the voltage, which sets in across the element when this has been charged or discharged by a certain current for a certain time, depends substantially exclusively on the capacitance of the element.

The relationship between the change in length of the element, the voltage setting in and the capacitance of the element can be expressed mathematically by

$$\Delta l = d_{33} \cdot u = d_{33} \cdot \frac{1}{C_p} \cdot i_n \cdot t_n$$

wherein

Δl represents the change in length of the piezo-electric element,
d_{33} the piezo-electric charge constant,
u the voltage setting in across the element,
C_p the capacitance of the element,

i_n the charging or discharging current during the actual charging or discharging operation and

t_n the charging or discharging time during the actual charging or discharging operation.

If the change in length which the element reaches after a certain time during charging or discharging by a predetermined charging or discharging current does not correspond with a target value, then a correction factor is computed from the deviation of the actual value from the target value, in particular a correction factor by which the current must be multiplied in order to ascertain the current by which the element must be charged or discharged for the predetermined time in order to experience the target change in length. The charging or discharging current to be used can, of course, also be ascertained by reference to a corresponding table or in other mode and manner. In order to avoid unduly large steps in the charging or discharging current, attenuation factors and/or threshold values for the correction factor and/or the charging or discharging current can be provided.

It is even simpler if the adaptation of the charging or discharging current to the capacitance of the element is based not on the change in length of the element, but on the time during which the element must be charged or discharged until a predetermined voltage sets in across it. The correction factor, by which the current i_{n-1} used during the (n-1)th charging or discharging operation must be multiplied in order to ascertain by which current i_n the element must be charged or discharged for the predetermined time during the next (n)th charging or discharging operation, in order to be brought to the predetermined voltage, then results as

$$\frac{t_{n-1}}{t_{soll}}$$

wherein

t_{n-1} is the time during which the element would have to be charged or discharged with the current i_{n-1} in order to be brought to the predetermined voltage and t_{soll} is the time after which the element should be brought to the predetermined voltage during the charging or discharging.

This means that the charging or discharging current i_n to be used during the nth charging or discharging operation is calculated by

$$i_n = i_{n-1} \cdot \frac{t_{n-1}}{t_{soll}}$$

Here, too, attenuation factors or threshold values for the correction factor and/or the charging or discharging current can be provided.

The adaptation of the charging or discharging current to the capacitance of the piezo-electric element on the basis of the time needed for reaching a predetermined voltage is simpler than an adaptation based on the change in length of the element, because the measurement of voltage and time is simpler than the measurement of the change in length.

Independently of the basis of the adaptation, it can be provided that the piezo-electric element experiences a predetermined change in length by the charging and discharging during a predetermined time. This is very advantageous because:

1)   the piezo-electric element always excites the system containing this in exactly the same manner and

2)   the system is prevented from being set into oscillations due to deviations from the desired course of movement of the element, i.e. too rapid or too slow and/or too great or too small expansion or contraction of the same.

That the thus-determined charging or discharging current actually flows, can be achieved by a control or regulating device, wherein the current flow is set during the control or regulation by opening and closing the charging or discharging switch at appropriate frequency and for appropriate durations.

A charging and discharging of the element as illustrated by way of example in Fig. 6 is thus obtained by the control or regulation. In Fig. 6, the curve A represents the course of the voltage setting in across the piezo-electric element, the curve B represents the current by which the element is charged or discharged, the curve C represents the switching state of the charging switch and the curve D represents the switching state of the discharging switch.

With the repeated closing and opening of the charging switch (curve C) as shown, there results a fluctuating charging current (curve B) which, however, has a constant mean value and by which a voltage (curve A) rising uniformly in the mean to a preset final value sets in across the element. Similarly, due to closing and opening of the discharging switch (curve D) repeatedly as shown, a fluctuating discharging current (curve B) results, which is constant in mean value and through which a voltage (curve A) dropping uniformly in the mean to a preset final value sets in.

The mean charging and discharging current and also the voltage to which the element is to be charged or to be discharged are variable and can be determined not only in dependence on the capacitance of the element, but also in dependence on the quantity of fuel to be injected per injection operation, the rotational speed of the engine, the pressure in the common rail or the engine temperature.

In a further embodiment, charging and discharging of the piezo-electric element 1 take place with a multistage drive control, i.e. the charging switch 3 or the discharging switch 5 is closed and opened repeatedly during the charging or discharging operation. In the illustrated embodiment, to which Fig. 8 refers, a two-step drive control takes place, i.e. the charging switch 3 or the discharging switch 5 is controlled twice in drive. In Fig. 8, the curve denoted by A represents the course of the voltage setting in across the piezo-electric element, the curve B represents the current by which the element is charged or discharged, the curve C represents the switching state of the charging switch and the curve D represents the switching state of the discharging switch.

With the closing and opening of the charging switch (curve C) twice, there results a twice rising and falling charging current (curve B), through which a voltage (curve A) rising in two steps to a preset final value sets in across the element. With the closing and opening of the discharging switch (curve D) taking place twice, there results a discharging current (curve B) falling and rising twice, through which a voltage (curve A) falling in two steps to a preset final value sets in.

The charging or discharging currents, the time durations of the individual drive controls, and the voltage, to which the element is to be charged or discharged are variable and can be determined not only in dependence on the capacitance of the piezo-electric element,

but also in dependence on the quantity of fuel to be injected per injection operation, the rotational speed of the engine, the pressure in the common rail or the engine temperature.

The components are dimensioned in such a manner that the desired voltage level is reached each time by one switching operation. The number of the switching operations can thus be reduced. Apart from a steady voltage course, electromagnetic interferences and switching losses are low. Moreover, the drive control of the power switches is appreciably simplified. A complex computation of the switching times can be dispensed with.

CLAIMS

1.   A method of influencing operation of a piezo-electric element, comprising the step of causing a current charging the element or a current discharging the element to be set in dependence on the capacitance of the element.

2.   A method as claimed in claim 1, wherein the charging and discharging current is varied in dependence on the instantaneous capacitance of the element.

3.   A method as claimed in claim 1 or claim 2, wherein the charging and discharging current is varied in dependence on the difference between the capacitance of the element and a target value for the capacitance.

4.   A method as claimed in claim 3, wherein said difference is a difference resulting from change in length of the element during charging or discharging thereof.

5.   A method as claimed in claim 3, wherein said difference is a difference resulting from the time required for charging or discharging the element to bring the element to a predetermined voltage.

6.   A method as claimed in any one of the preceding claims, comprising the step of determining a charging or discharging current to be used in a succeeding charging or discharging operation for the element by multiplying the current used in the preceding operation by a correction factor.

7.   A method as claimed in claim 6, comprising the step of determining the correction factor in dependence on the ratio of actual values of magnitudes measured during or after a charging or discharging operation to target values for these magnitudes.

8.   A method as claimed in claim 6, wherein the correction factor or the charging or discharging current is limited in its magnitude or changes in its magnitude by the use of threshold values or attenuation factors.

9.   A method as claimed in any one of the preceding claims, wherein the charging or discharging current is kept substantially constant during a charging or discharging operation.

10.   A method as claimed in claim 1 and substantially as hereinbefore described with reference to the accompanying drawings.

11.   Means for influencing operation of a piezo-electric element, comprising control or regulating means for causing a current charging the element or a current discharging the element to be set in dependence on the capacitance of the element.

Application No:	GB 9902928.2	Examiner:	K. Sylvan
Claims searched:	1-11	Date of search:	20 April 1999

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

    UK Cl (Ed.Q): H3P (PCCD)

    Int Cl (Ed.6): H01L (41/04)

Other:

Documents considered to be relevant:

Category	Identity of document and relevant passage		Relevant to claims
X,P	WO98/27600 A1	Siemens. See the abstract and figure 3.	1,3,4,11
X	US5479062	Fujitsu. See abstract and column 6 lines 50-61.	1,6,7,11
X	US5387834	Brother. See abstract	1,3,4,11
X	US4628275	Rockwell. See figure 4 and column 6 lines 5-10.	1-4,9,11